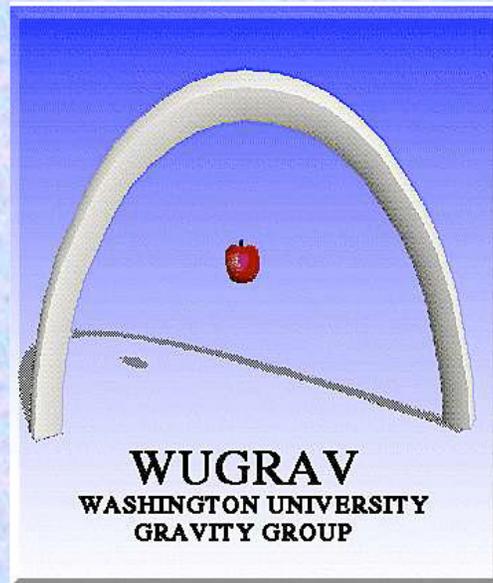


Fundamental Gravitational Physics in the LISA Time Frame



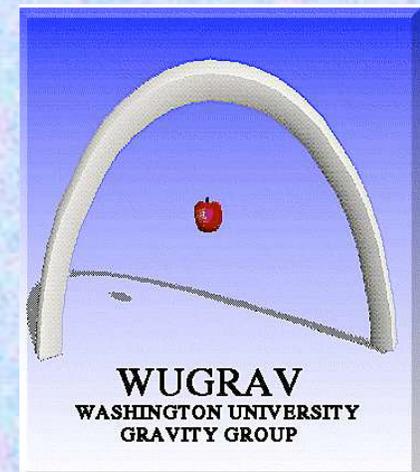
Clifford Will

Washington University, St. Louis

6th LISA Symposium, June 19-23 2006

Fundamental Gravitational Physics in the LISA Time Frame

- Introduction
- The Einstein Equivalence Principle
- Solar-System Tests of GR
- Binary Pulsar and Strong-Field Tests of GR
- Gravitational Waves -- A New Testing Ground



6th LISA Symposium

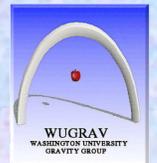
The Einstein Equivalence Principle

- Test bodies fall with the same acceleration
Weak Equivalence Principle (WEP)
- In a local freely falling frame, physics (non-gravitational) is independent of frame's velocity
Local Lorentz Invariance (LLI)
- In a local freely falling frame, physics (non-gravitational) is independent of frame's location
Local Position Invariance (LPI)

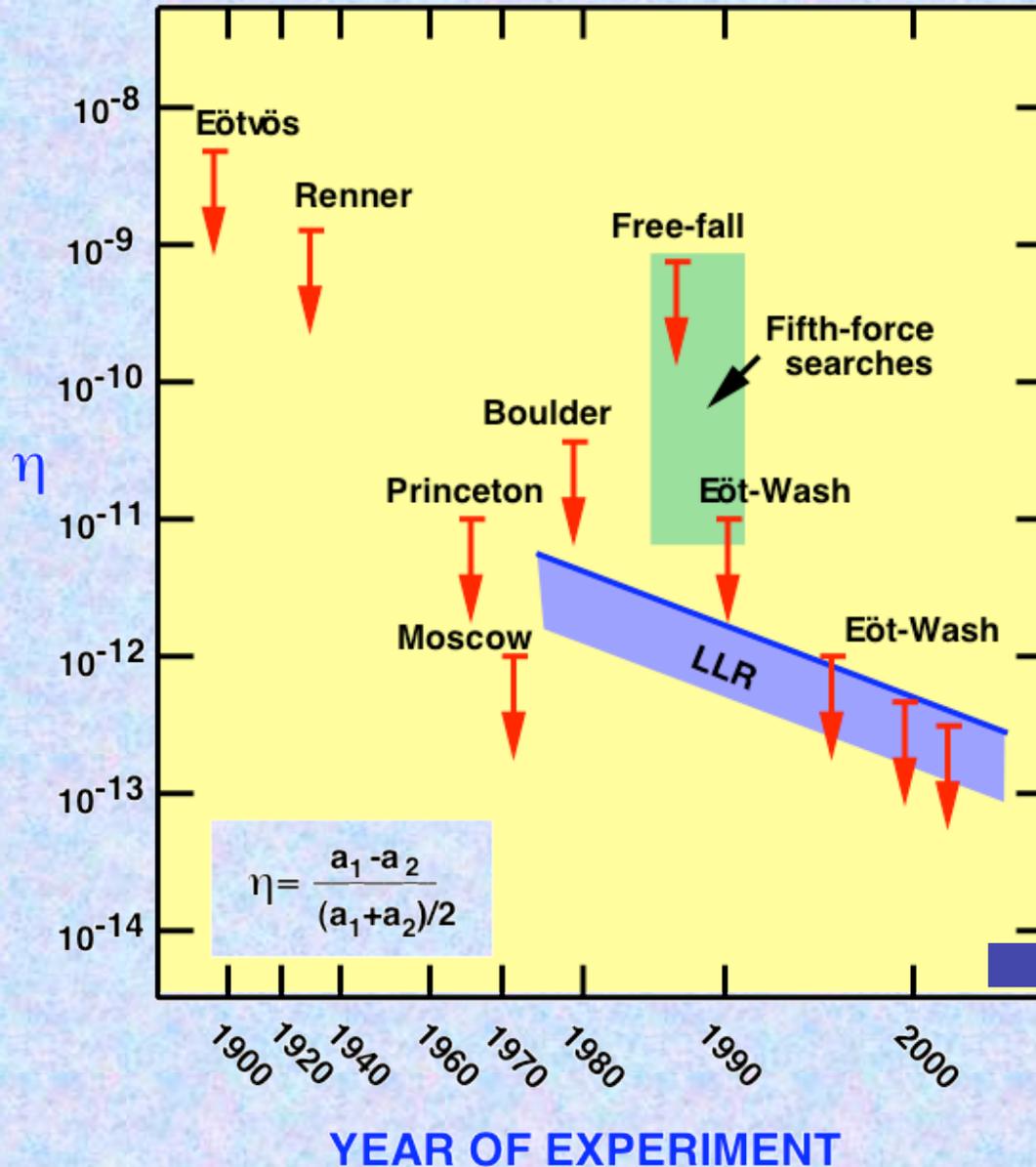
EEP ~ Metric theory of gravity

- $\eta_{\mu\nu}$ locally ~ symmetric $g_{\mu\nu}$
- "comma" ~ "semicolon"

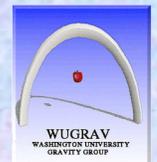
Gravity = Geometry



Tests of the Weak Equivalence Principle

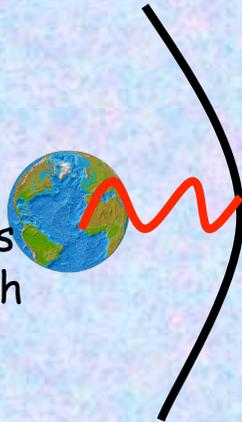


APOLLO (LLR) 10⁻¹³
 Microscope 10⁻¹⁵(2008)
 STEP 10⁻¹⁸ (?)

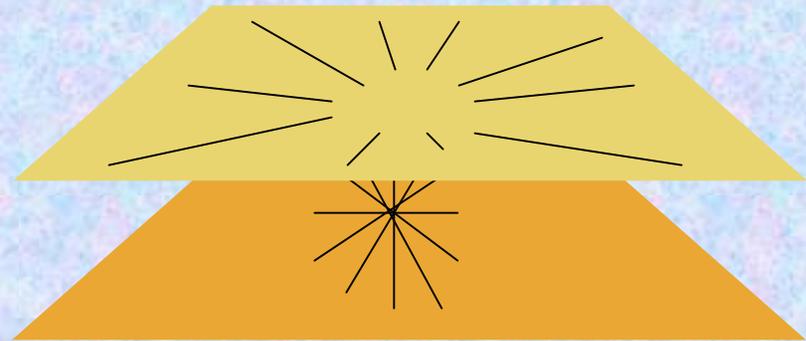


5th Force, Strings, Extra Dimensions and EEP

- exchange of scalar or vector bosons of mass m
- ultra-small mass for long range effects
- gravitational strength coupling



- Gravity "leaks" into extra dimensions of macroscopic scale ($1/r^2 \rightarrow 1/r^n$)

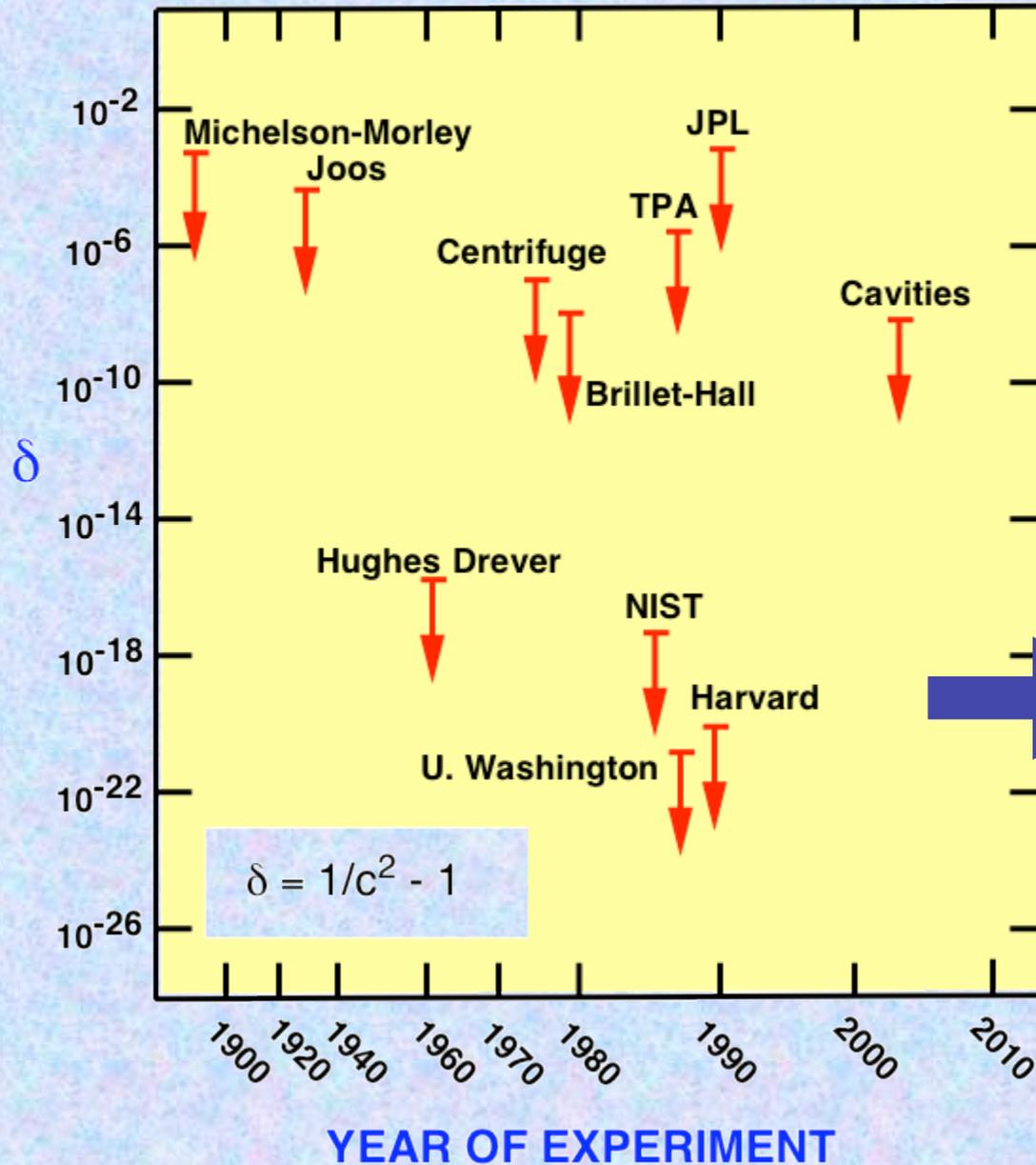


$$V_{AB}(r) \propto \frac{(1 + \alpha_{AB} e^{-\frac{r}{\lambda}})}{r}$$

No evidence to 1/100 of gravity at 1 mm & to 1 X gravity At 10 μm

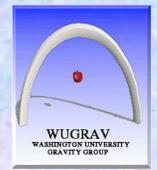
Violation of EEP or Inverse Square Law could signal new physics

Tests of Local Lorentz Invariance

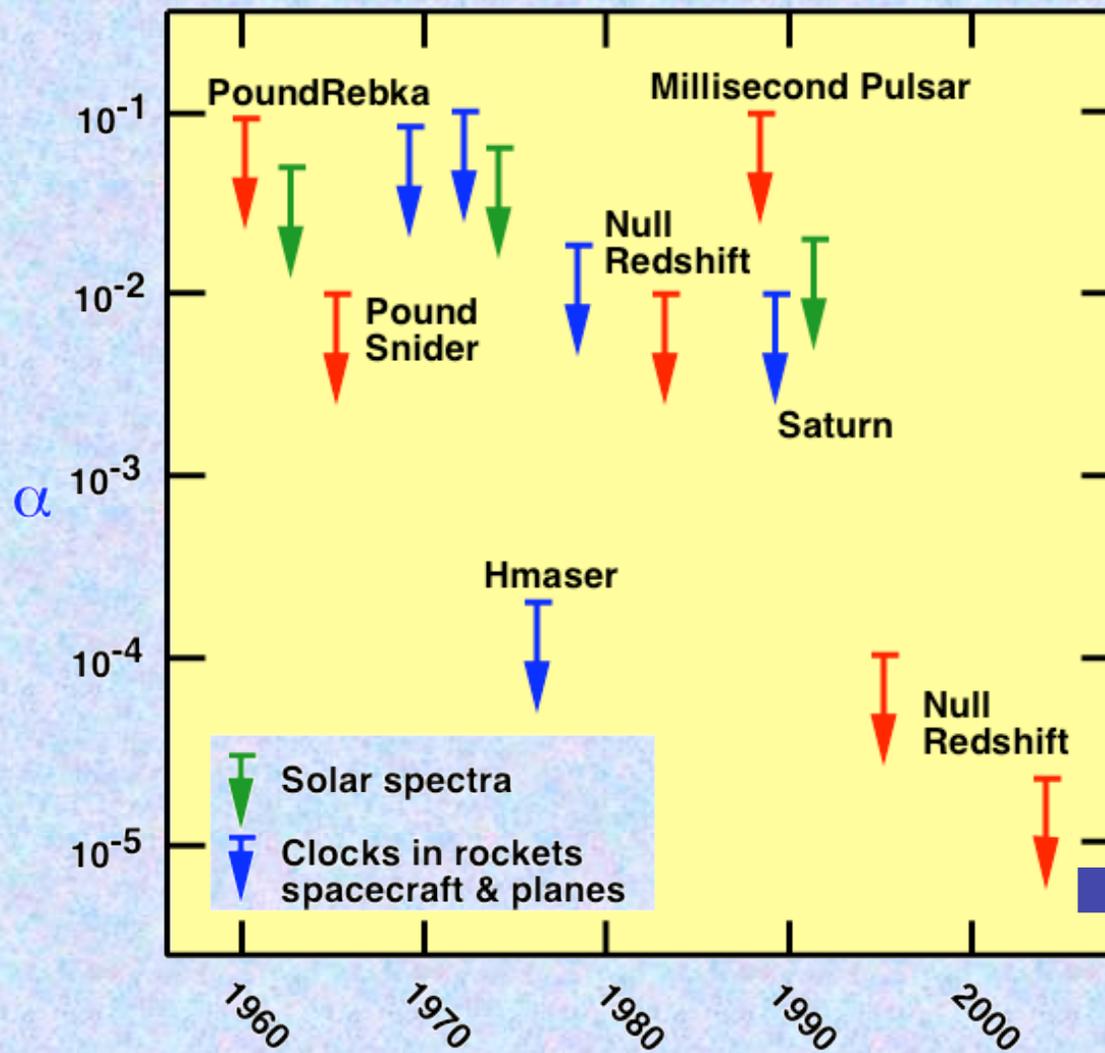


Extended frameworks by Kostelecky, Jacobson *et al.*

- Clock comparisons
 - ACES (2010)
- Clocks vs cavities
- Time of flight of high energy photons
- Birefringence in vacuum
- Neutrino oscillations
- Threshold effects in particle physics



Tests of Local Position Invariance



ACES(2010) 10^{-6}

YEAR OF EXPERIMENT

$$\Delta\nu/\nu = (1+\alpha)\Delta U/c^2$$

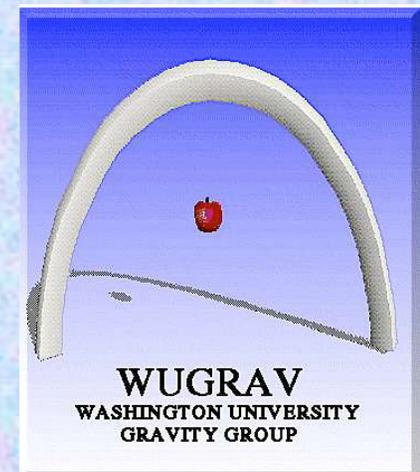


Tests of Local Position Invariance

Constant	Limit (yr ⁻¹)	Z	Method
α	$<30 \times 10^{-16}$	0	Clock comparisons
	$<0.5 \times 10^{-16}$	0.15	Oklo reactor
	$<3.4 \times 10^{-16}$	0.45	¹⁸⁷ Re decay
	$(6.4 \pm 1.4) \times 10^{-16}$	3.7	Quasar spectra
	$<1.2 \times 10^{-16}$	2.3	Quasar spectra
α_W	$<1 \times 10^{-11}$	0.15	Oklo reactor
	$<5 \times 10^{-12}$	10 ⁹	BBN
m_e/m_p	$<3 \times 10^{-15}$	2-3	Quasar spectra

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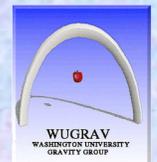
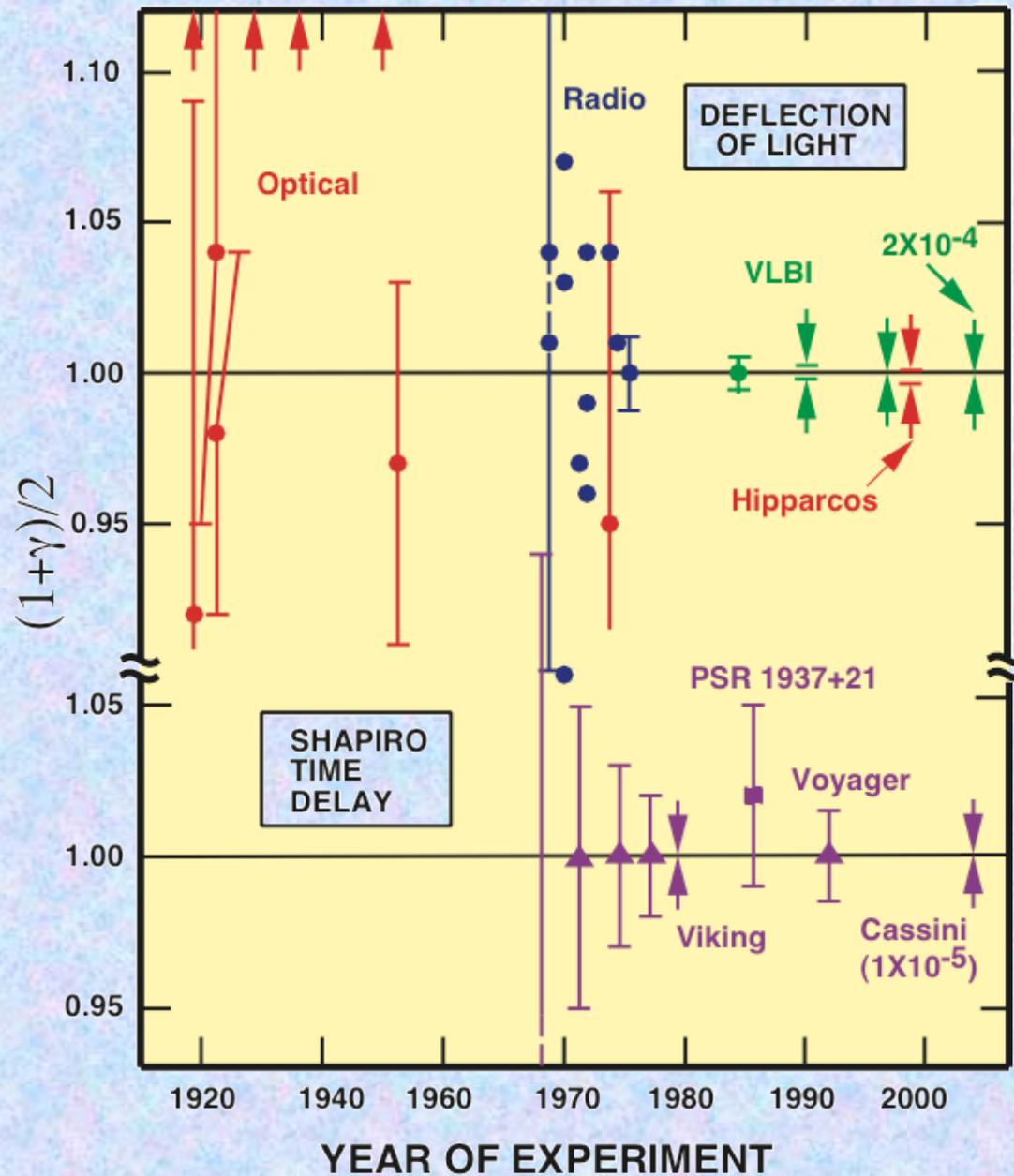


6th LISA Symposium

PPN Parameters and their Significance

Parameter	What it measures, relative to general relativity	Value in GR	Value in scalar tensor theory	Value in semi-conservative theories
γ	How much space curvature produced by unit mass?	1	$(1+\omega)/(2+\omega)$	γ
β	How "nonlinear" is gravity?	1	$1 + \Lambda$	β
ξ	Preferred-location effects?	0	0	ξ
α_1	Preferred-frame effects?	0	0	α_1
α_2		0	0	α_2
α_3		0	0	0
ζ_1	Is momentum conserved?	0	0	0
ζ_2		0	0	0
ζ_3		0	0	0
ζ_4		0	0	0

The parameter $(1+\gamma)/2$



Bounds on the PPN Parameters

Parameter	Effect or Experiment	Bound	Remarks
$\gamma - 1$	Time delay	2.3×10^{-5}	Cassini tracking
	Light deflection	4×10^{-4}	VLBI
	Perihelion shift	3×10^{-3}	$J_2 = 2 \times 10^{-7}$
	Nordtvedt effect	5×10^{-4}	$LLR \Delta a < 3 \times 10^{-4}$
	Earth tides	10^{-3}	grav
	Polarization	10^{-4}	LLR
	Spin precession	2×10^{-4}	
		4×10^{-7}	
α_3	Self-acceleration	10^{-20}	
ζ_1	--	10^{-8}	Combined
ζ_2	Binary d		PSR 1913+16
ζ_3	Newton's 3rd		Lunar acceleration
ζ_4	--		Not independent

GAIA (2011) 10^{-6}
LATOR 10^{-8}

APOLLO 3×10^{-5}

BepiColombo (2012)
 $J_2 \sim 10^{-8}$

$$\eta = 4\beta - \gamma - 3 - 10\xi/3 - \alpha_1 + 2\alpha_2/3 - 2\zeta_1/3 - \zeta_2/3$$

Bound on scalar-tensor gravity: $\omega > 40,000$



GRAVITY PROBE B

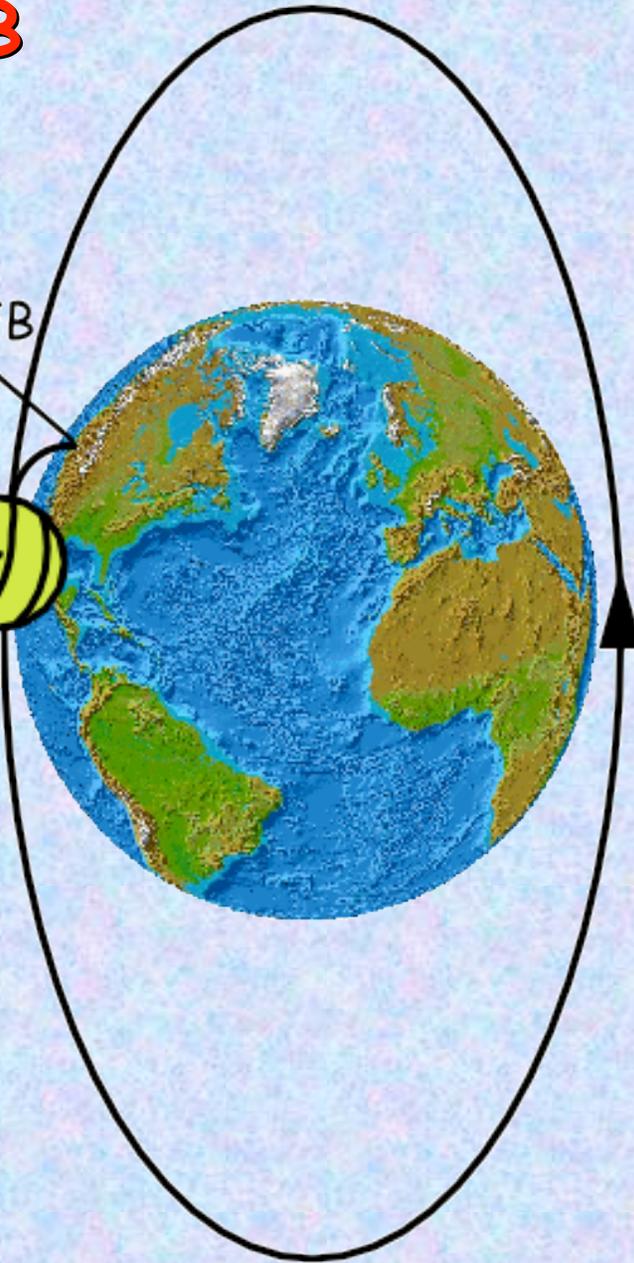
Guide star



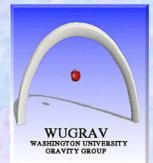
Launch VAFB

42 mas/yr
(frame
dragging)

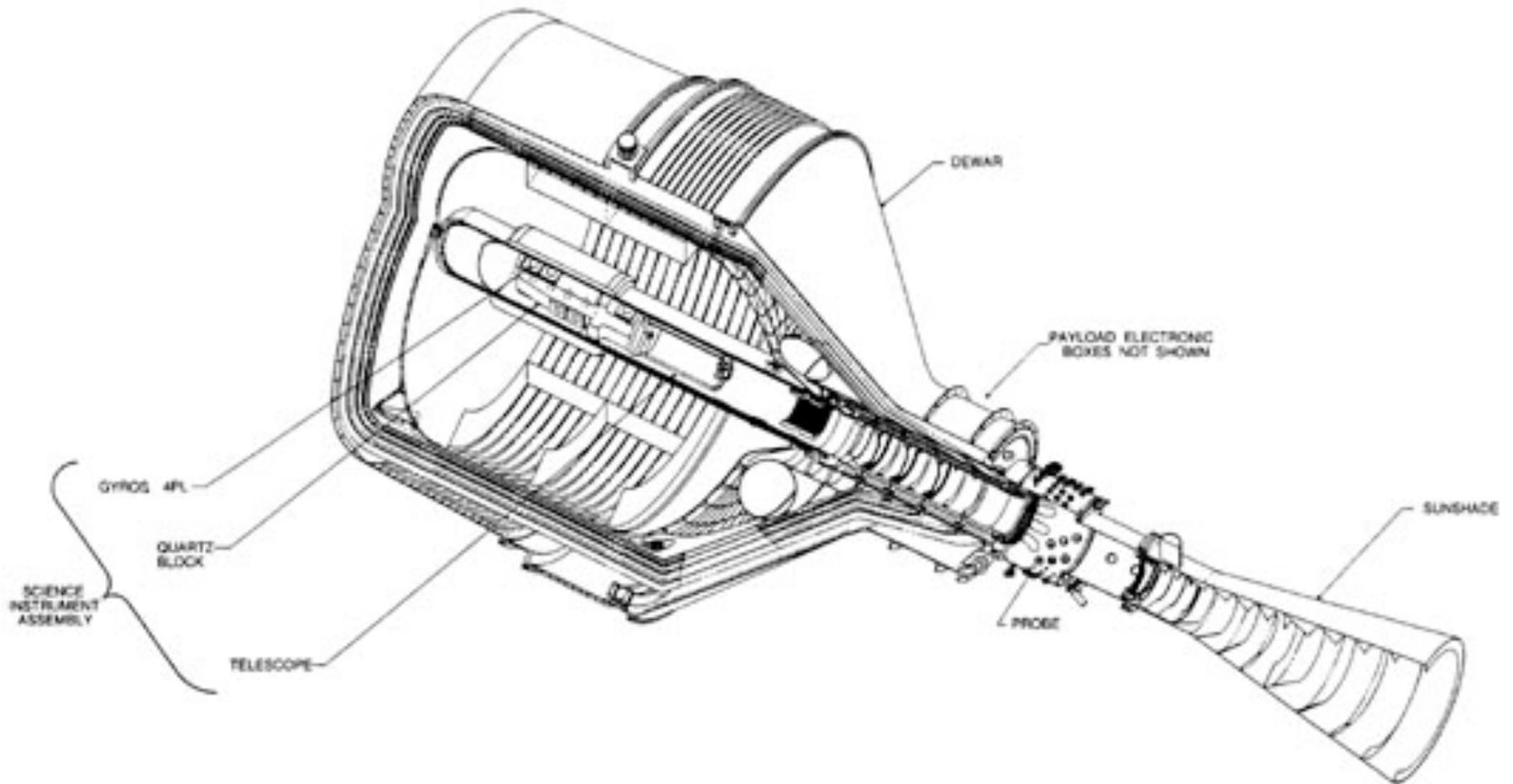
6600
mas/yr
(geodetic)



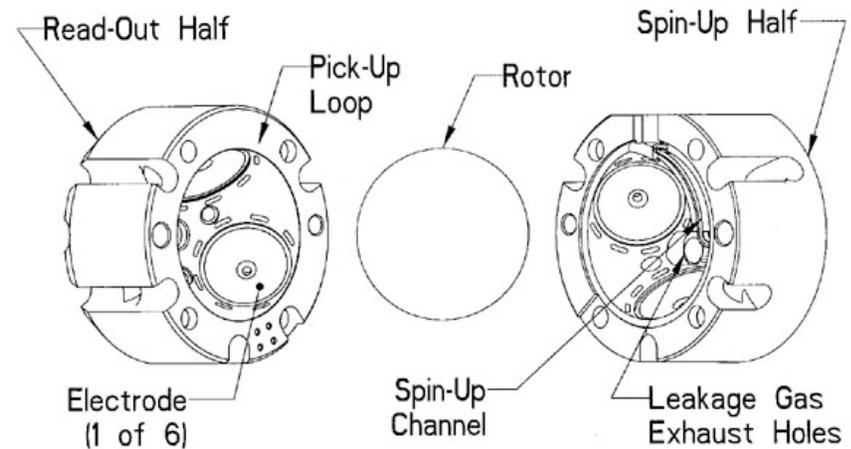
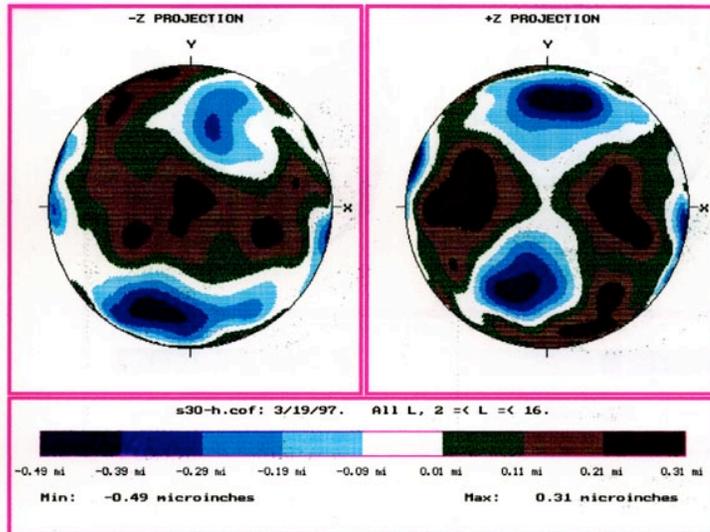
Goal 0.4 mas/yr
Launch April 20, 2004
Mission ended Sept 2005



Gravity Probe B: The Experiment -- Payload

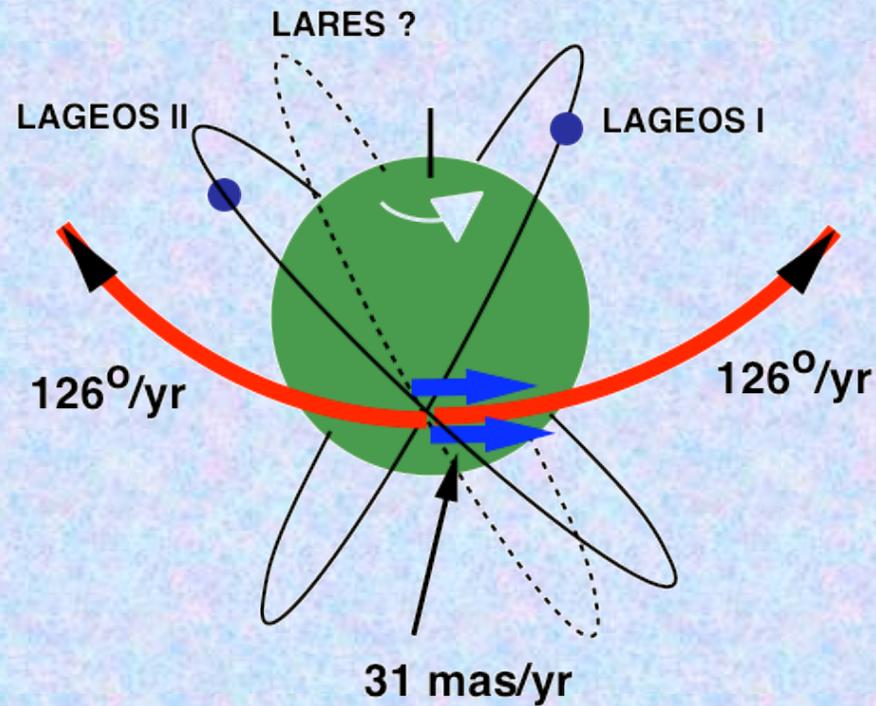


Gravity Probe B: The Experiment -- Gyroscopes



LAGEOS TEST OF FRAME DRAGGING

Measure precession of node (Newton + FD)



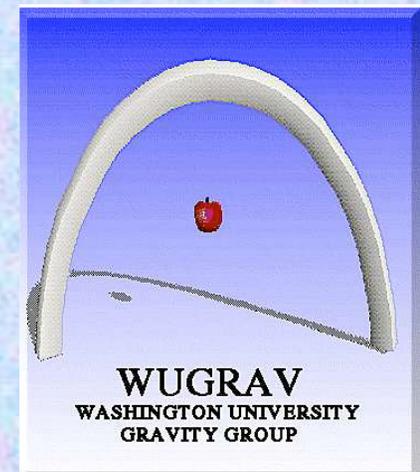
Existing LAGEOS I and II:

- measure Ω_I, Ω_{II}
- fit J_2, α_{FD}
- use measured J_n ($n > 2$)
- 10% precision (?)

LARES (Phase A)

The Confrontation between General Relativity and Experiment

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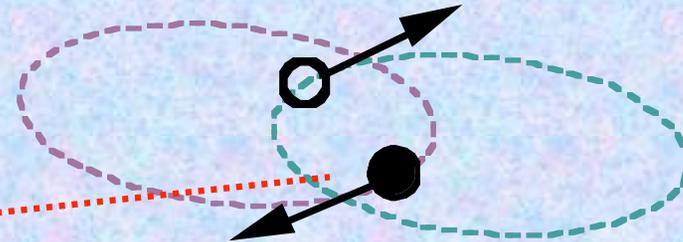
J. A. Wheeler School

The Binary Pulsar: Gravitational Waves Exist!

Discovery: 1974

Pulse period: 59 ms (16cps)

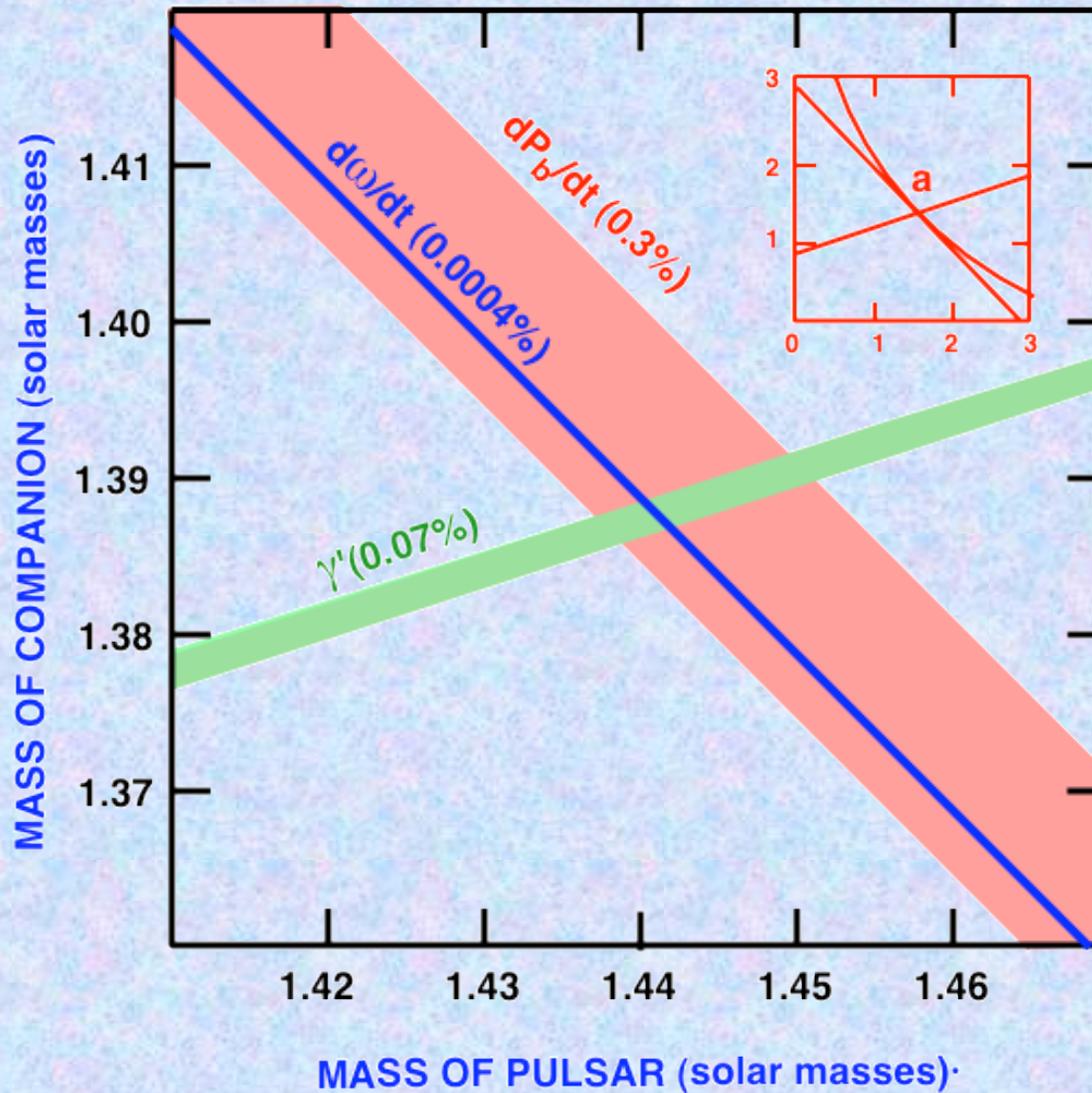
Orbit period: 8 hours



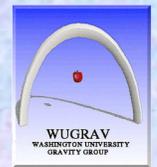
Parameter	Value
Keplerian	
Pulse Period (ms)	59.029997929613(7)
Orbit Period (days)	0.322997448930(4)
Eccentricity	0.6171338(4)
Post-Keplerian	
Periastron Shift ($d\omega/dt$ °/yr)	4.226595(5)
Pulsar Clock Shifts (ms)	4.2919(8)
Orbit Decay (dP_b/dt 10^{-12})	-2.4184(9)



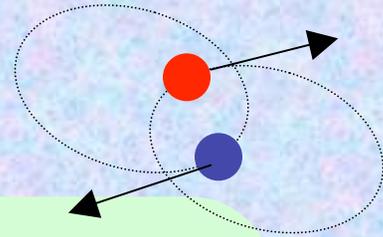
PSR 1913+16: Concordance with GR



$$m_p = 1.4411(7) M_{\text{sun}} \quad m_c = 1.3874(7) M_{\text{sun}}$$



The Binary Pulsar Zoo

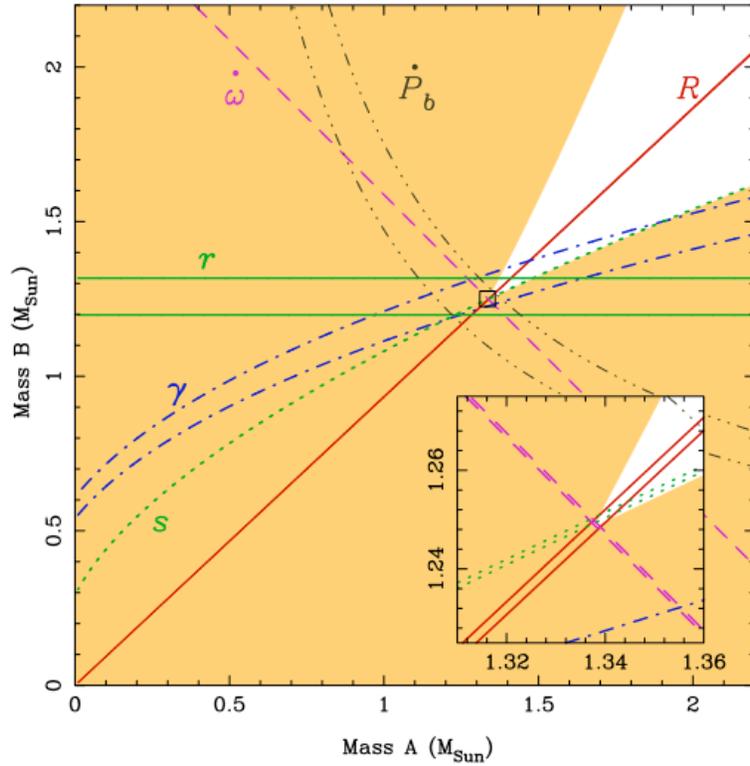


PSR 2127+11C

- a clone of 1913+16

PSR

- c



J

- 0

- t

- d

- s

- d

- $dP_b/dt \sim 0\%$

J 1141-6545

- 0.19 day orbit

- $1 M_\odot$ WD companion

- $dP_b/dt \sim 25\%$

$dP_b/dt \rightarrow 2\%$
 $\Rightarrow \omega > 40,000$

1756-2251

- 0.32 day orbit

1906+0746

- 0.16 day orbit

0751+1807

- $M_1 = 2.1 \pm 0.2 M_\odot$

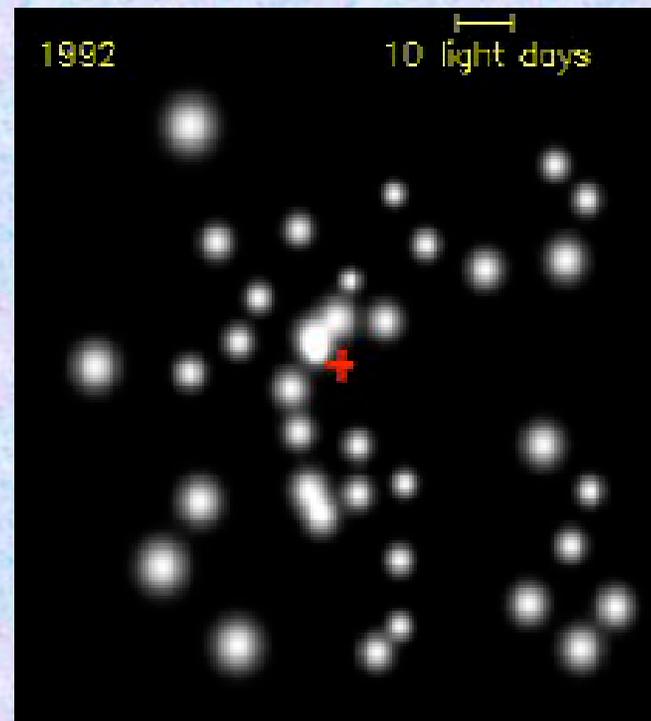


Probing BH spacetime using stars

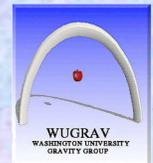
A 3.6 million M_{sun} black hole in the Milky Way

Next generation adaptive optics
telescopes (eg GRAVITY - VLTI)

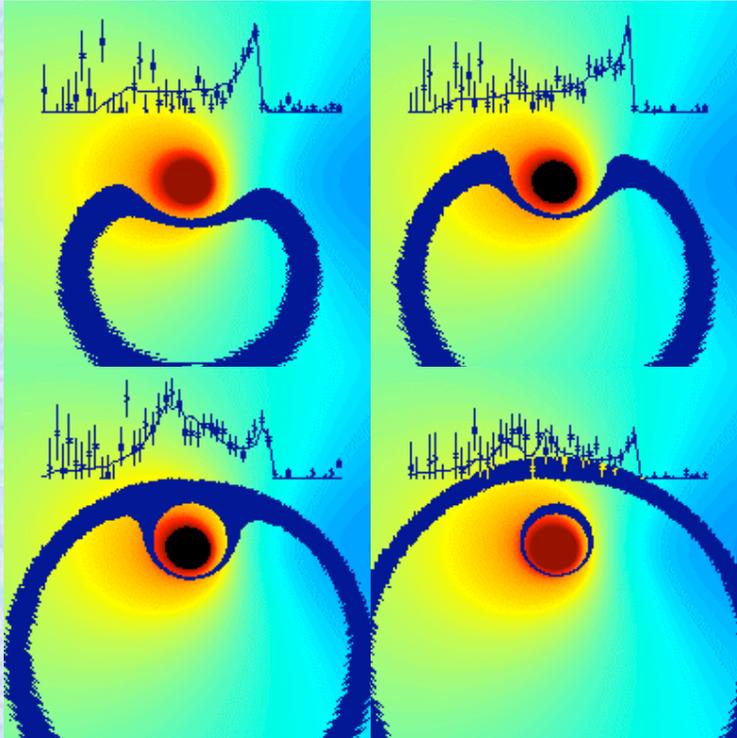
- 10 μas precision
- faint stars
- periods ~ 1 year
- pericenter $100 R_s$
- measure pericenter shift, frame dragging orbit precession



Genzel et al, Max Planck Institute
Ghez et al, UCLA



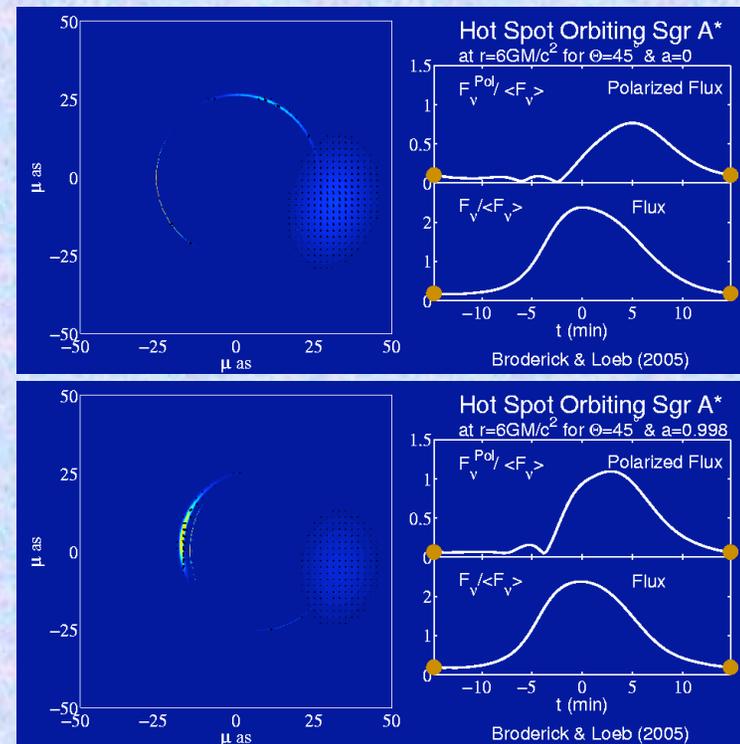
Imaging and Spectroscopy of Accretion Disks



C. Reynolds, U. Md

- Evolution of Fe fluorescence lines during X-ray flare
- sensitive to M and J of BH
- Constellation-X mission

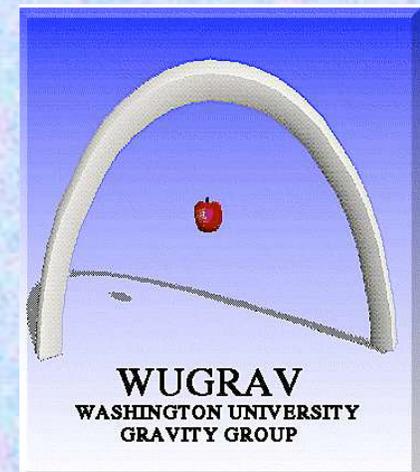
- High resolution imaging of hot spot in accretion onto BH at Galactic Center
- 45° inclination
- $a=0$ and 0.998



Broderick & Loeb, CFA

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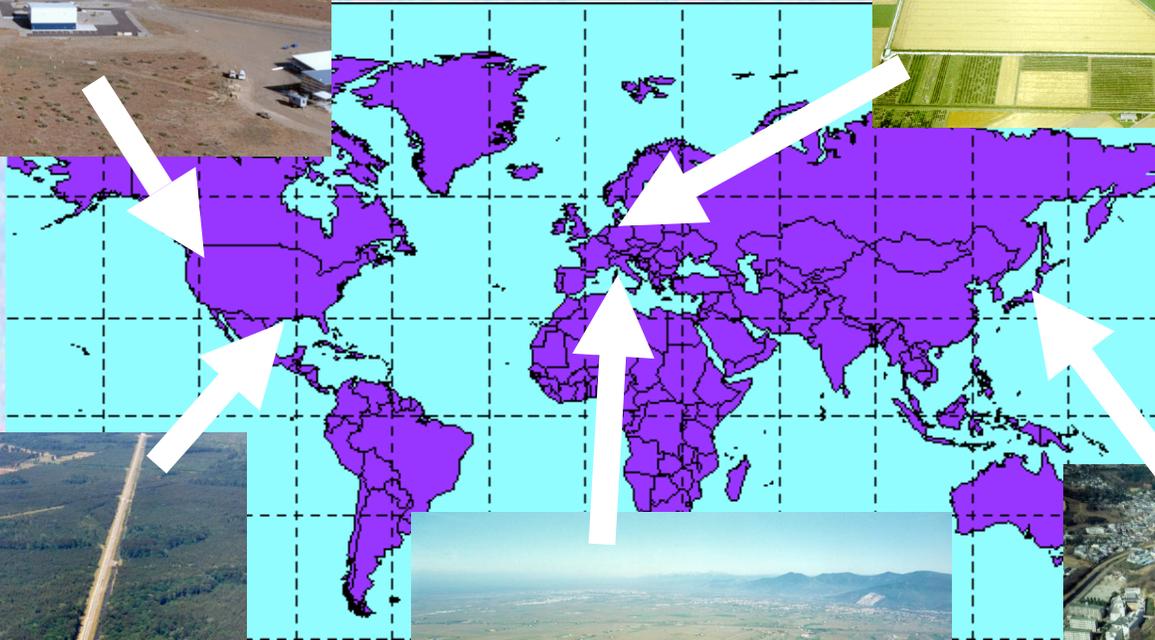
6th LISA Symposium

Interferometers Around The World

LIGO Hanford 4&2 km



GEO Hannover 600 m



LIGO Livingston 4 km



Virgo Cascina 3 km



TAMA Tokyo
300 m

Inspiralling Compact Binaries - Strong-gravity GR tests?

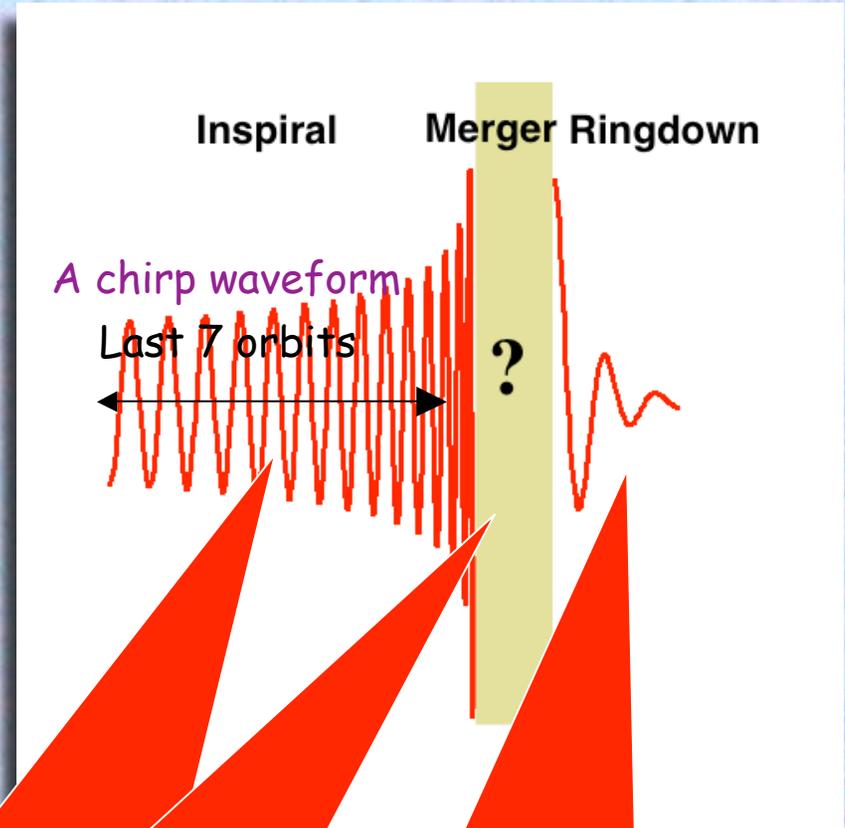
- Fate of the binary pulsar in 100 My
- GW energy loss drives pair toward merger

LIGO-VIRGO

- Last few minutes (10K cycles) for NS-NS
- 40 - 700 per year by 2010
- BH inspirals could be more numerous

LISA

- MBH pairs ($10^5 - 10^7 M_\odot$) in galaxies
- Waves from the early universe



Comparing
detailed

[Schar

See

Merging horizons
spacetime
solutions of

See talks by
Campanelli &

Uniquely determined by
M and S of hole - test
of GR's black holes?

[Berti, Cardoso & CW]

See talk by Berti (T)



GW Phasing as a precision probe of gravity

$$\Psi(f) = 2\pi f t_c - \Phi_c - \pi/4$$

N $+\frac{3}{128} u^{-5/3} [1$ Measure chirp mass \mathcal{M}

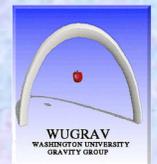
1PN $+\frac{20}{9} \left(\frac{743}{336} + \frac{11}{4} \eta \right) \eta^{-2/5} u^{2/3}$ Measure m_1 & m_2

1.5PN $-16\pi u$ "Tail" term - test GR

2PN $+10 \left(\frac{305673}{1016064} + \frac{5429}{1008} \eta + \frac{617}{144} \eta^2 \right) \eta^{-4/5} u^{4/3}$ Test GR

$+ O(u^5)]$

$M = m_1 + m_2$	$\eta = m_1 m_2 / M^2$	$\mathcal{M} = \eta^{3/5} M$
$u = \pi \mathcal{M} f \sim v^3$		



Speed of Waves and Mass of the Graviton

Why Speed could differ from "1"

- massive graviton: $v_g^2 = 1 - (m_g/E_g)^2$
- $g_{\mu\nu}$ coupling to background fields: $v_g = F(\phi, K^\alpha, H^{\alpha\beta})$
- gravity waves propagate off the brane

Examples

- General relativity. For $\lambda \ll R$, GW follow geodesics of background spacetime, as do photons ($v_g = 1$)
- Scalar-tensor gravity. Tensor waves can have $v_g \neq 1$, if scalar is massive
- Massive graviton theories with background metric. Circumvent vDVZ theorem. Visser (1998), Babak & Grishchuk (1999, 2003)

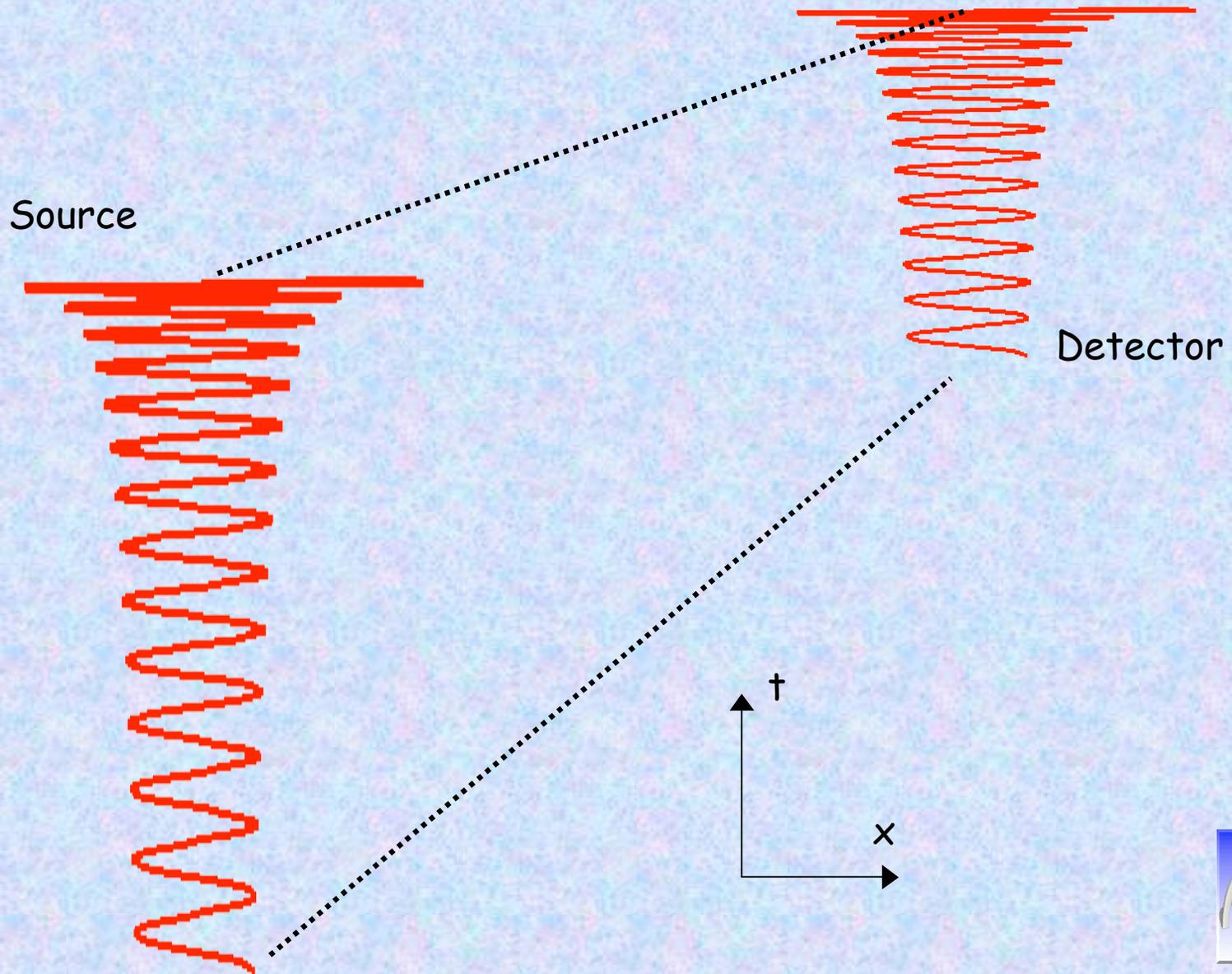
Possible Limits

$$1 - v_g \approx 5 \times 10^{-17} \frac{200 \text{ Mpc}}{D} [\Delta t_a - (1 + Z)\Delta t_e]$$

D = distance of source, Z = redshift, Δt_a (Δt_e) = time difference in seconds



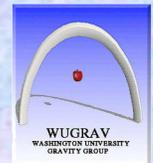
Bounding the graviton mass using inspiralling binaries



Bounding the graviton mass using inspiralling binaries

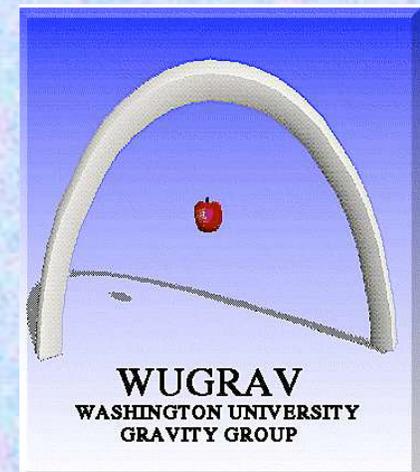
m_1	m_2	Distance(Mpc)	Bound on λ_g (km)
Ground-Based (LIGO/VIRGO)			
1.4	1.4	300	4.6×10^{12}
10	10	1500	6.0×10^{12}
Space-Based (LISA)			
10^7	10^7	3000	6.9×10^{16}
10^5	10^5	3000	2.3×10^{16}

Other methods	Comments	Bound on λ_g (km)
Solar system $1/r^2$ law	Assumes direct link between static λ_g and wave λ_g	3×10^{12}
Galaxies & clusters	Ditto	6×10^{19}
CWDB phasing	LISA (Cutler et al)	1×10^{14}



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